Advanced Solar- and Laser-pushed Lightsail Concepts

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Abstract

Beam-pushed propulsion systems, such as solar- laser-, or microwave- pushed sails, allow the possibility of fuel-free propulsion in space. This makes possible missions of extremely high delta=V, potentially as high as 30,000 km/sec (0.1c), which is required for an fly-by mission to a nearby star.

This project analyzed the potential use of dielectric thin films for solar and laser sails. The advantages are extremely light weight and good high temperature properties, which are necessary for both for solar-sail missions inward toward the sun, for solar sail missions outward from the sun that use a close perihelion pass to build speed, and for high velocity laser-pushed missions for the outer solar system and for interstellar probes. Because of the higher temperature capability, the sails can operate under higher laser illumination levels, and hence achieve higher acceleration. This allows large decreases in the minimum size of the sail required.

The project also made an analysis of the possibility of microwave-pushed sail propulsion. Microwave sails have the advantage that high-power microwave sources are already existing technology. The study made a new re-analysis of a concept proposed by Robert Forward, and found that a carbon mesh sail is preferable to the aluminum sail proposed by Forward, due to better high-temperature properties.

Beam propulsion concepts can be used for lower delta-V missions as well. Candidate missions include fast-transit missions to the outer planets, Kuiper and Oort cloud missions, and interstellar precursor missions.

The preliminary analysis indicates that the power required for an interstellar mission using a laser-pushed lightsail could be reduced to 448 MW by the use of a dielectric sail. This is a considerable reduction from the 65 GW required for the baseline mission. It makes the power requirement for the interstellar mission an amount that can be achieved in the reasonable future, and not an unreasonable amount which would require nearly a hundred dedicated electrical power plants.

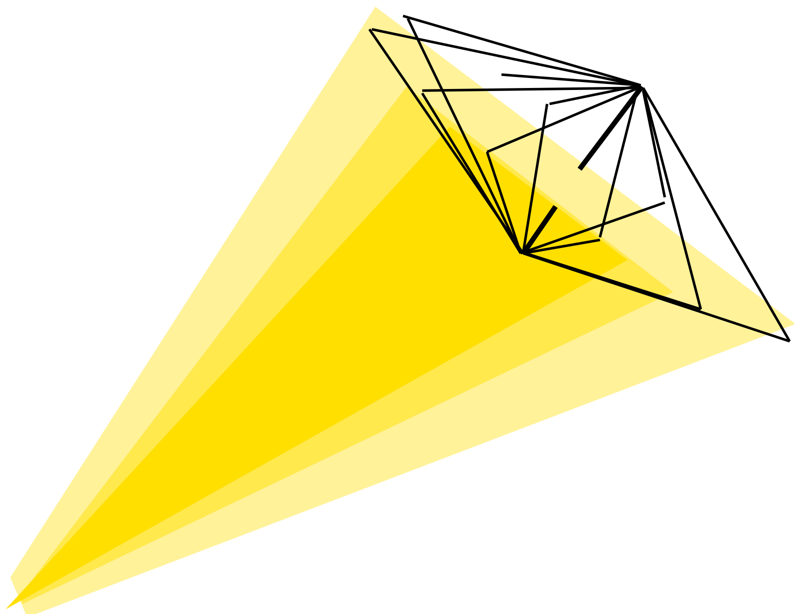

Figure 1: conceptual view of a beam-pushed interstellar probe

1.0 INTRODUCTION

Envision a future of space exploration, featuring featherweight microprobes on iridescent sails, tiny vehicles sailing on solar power with trip times of a few weeks to Mars or Venus-- a month to Jupiter-- with the assistance of a laser push, trip times of a month or so to the outer planets and Pluto. Exploration of the Oort cloud and the fringes of interstellar space would be possible in only a year's travel time, and probes to the nearest stars, traveling at 10% of the speed of light, would return images of planets not generations later, but well within the lifetime of the people who launched them

Advanced solar- and laser-pushed lightsail concepts [figure 1] will be as a starting point for the development of revolutionary capabilities in spaceflight, with the potential for leaping well past the current technology to enable and expand the vision of NASA's long-range strategic plans.

Examining the challenges directed to advanced concepts, solar and laser-pushed lightsails will expand our capabilities by allowing us to directly address the following grand challenges:

■ *Space Science:* Help to solve the mysteries of the universe by use of probes which can enter the fringes of interstellar space with a short flight time, allowing probes to a thousand astronomical units and ten thousand astronomical units to expand our knowledge of the interstellar medium, the heliopause, and make parallax measurements of the distances to every star and object of interest in the galaxy.

■*Exploration of the solar system:* A propulsion system which will conduct comprehensive exploration of the entire solar system (including beyond the planets) with micro-sized laser- and solar-sail propelled vehicles.

■*Exploration beyond the solar system:*: Laser-pushed systems for future exploration, to observe planets around other stars directly and identify which, if any, may be Earthlike.

■*Search for life beyond Earth.* Search for life on planets of other stars by interstellar fly-by probes

■*Revolutionize our access to space.* Lightsails could be a means to deliver payloads on rendezvous missions to the outer planets within a ten-year mission time frame-- in fact, with a one-year or less travel time-- and to go beyond our solar system to interstellar distances well within a fifty-year horizon. A space propulsion system capable of continuous laser-pushed thrust to achieve very high speed, one that does not rely on an on-board propulsion system.

1.1 BACKGROUND

Interstellar Propulsion

Recently there has been a great deal of excitement engendered by the unexpected discovery of planetary systems around several stars. There has been considerable discussion of the proposed focused effort to detect Jupiter and even Earth-sized planets around nearby stars. After such extra-solar planetary systems are found, the natural next question will be: how can we send a probe there?

The obvious propulsion systems used for interplanetary probes are severely lacking in capability. To send an interstellar probe which will return information within the lifetime of the people who launched it requires a probe speed of at least 10% of the speed of light, or a ΔV of 30,000 km/sec, assuming a fly-by probe.

It hardly needs to be pointed out that a propulsion system to produce near-relativistic speeds would also make missions within the solar system, including the outer planets, the Kuiper belt and the Oort cloud, possible with flight times of days. Since this provides a possible near-term application for the technology, the project will examine applications to both solar-system and interstellar probes.

The velocity requirement immediately rules out chemical propulsion, and even nuclear thermal propulsion systems. Even a gas-core nuclear rocket operating with a specific impulse of 7000 seconds would require a mass ratio of nearly 10^{190}. Clearly, existing propulsion systems are inadequate.

Fusion rockets have been proposed with specific impulse ranging between 2500 and 270,000 seconds. At 270,000 seconds [Borowski 1987], a mass ratio of slightly over 80,000 would achieve the required velocity. In addition to the high mass ratio, though, such a fusion propulsion system has a number of difficulties, primary of which is that a technology for controlled fusion does not currently exist, and the development program is likely to be extremely expensive.

Use of antimatter for a rocket could solve the propulsion problem, but antimatter propulsion has significant technical difficulties. In addition to the difficulty of development of a propulsion system, low-mass methods for long-term antimatter storage need to be invented. An additional difficulty of antimatter is that to date, while both positrons and anti-protons can be produced (albeit in femto-gram quantities), an anti-hydrogen atom has yet to be made. The problem of how to produce usable quantities of antimatter for rocket propulsion is far beyond the scope of any project that could be achieved with funds available here.

1.11 Beamed-energy Propulsion

An alternative solution to the problem of the mass ratio required for high velocity flight is to use beamed-energy. In beamed-energy propulsion, the energy source is left stationary, and the probe is pushed at a distance. Since the propulsion system does not move, the weight of the energy source is not critical, and fuel does not have to be carried.

An example of the beamed-energy propulsion is the photon-pushed sail. Since a photon has momentum, a photon beam can “push” a reflective sail. In practical terms, the force produced by reflecting a light beam is 6.7 newtons per gigawatt of light reflected. This force comes with no expenditure of fuel whatsoever. Thus, it is extremely favorable for high delta-V missions.

It is noteworthy that the force produced is proportional only to the power density, and is independent of the wavelength. Two practical choices for photon-pushed sails have been proposed: light-pushed sails [Tsander 1924, Forward 1984, and others], and microwave-pushed sails [Forward 1985]. The microwave-pushed sail ("Starwisp") has advantages, however, it has several disadvantages. Probably the worst of these disadvantages is the difficulty of scale, which is an unavoidable consequence of the larger wavelength of microwaves compared to light: The 20 gram, 1-km diameter "Starwisp" probe proposed by Forward requires a focusing lens of 50,000 km diameter-- a structure four times the diameter of the Earth! Constructing such a lens is clearly a significant engineering project. The "Starwisp" proposal also assumes that, to achieve low resistance, the aluminum mesh could be kept at 40°K. This is an assumption which needs to be critically examined in view of the high (ten solar intensities) power density on the sail.

There are two options for a sail pushed by light, the solar-sail and the laser-pushed sail [figure 2]. Since these both typically operate in a similar region of the spectrum, the sails themselves are actually very similar, with the exception that a solar sail reflect a range of incident wavelength, while a laser sail must only be reflective for a single wavelength.

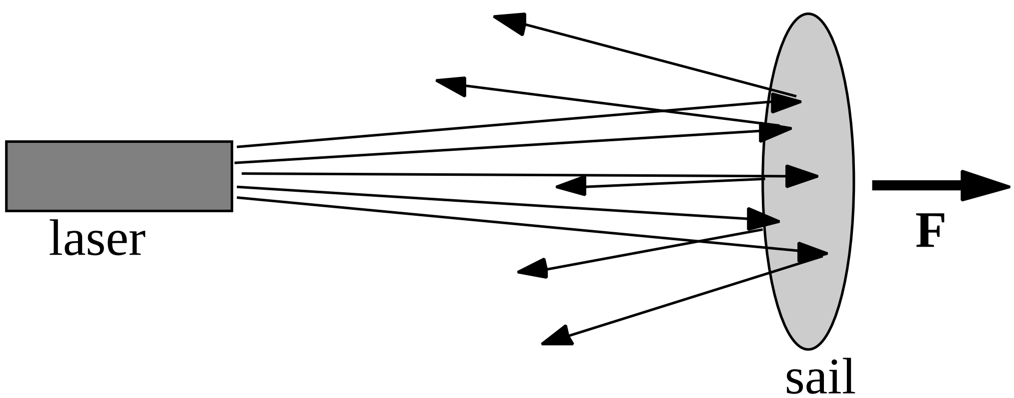

Figure 2: Laser-pushed lightsail (schematic)

1.12 Solar Sails

The first realization that a spacecraft could be propelled entirely without fuel by using the pressure of sunlight was by Tsander in 1924. A solar sail works by using the pressure of sunlight upon a large, lightweight reflective surface. While the force is extremely small, the thrust acts continuously for months, and in space, sunlight is abundant and free. Garwin in 1958 and Tsu in 1959 did analyses of the solar-sail concept and realized that it could be made practical. The literature on the subject since that time is large. Use of solar sails has been suggested for Mars missions [Staehle 1981], Mercury orbiters, comet and asteroid rendezvous [Friedman *et al.* 1978], and for interstellar probes [Matloff 1984A, 1984B; Mallove and Matloff 1989].

As typically proposed, a solar sail consists of a very thin sheet of plastic (typically Mylar) with a reflective metal (typically aluminum) layer. It is potentially an extremely simple and efficient method of space transportation. For a high-velocity mission, however, the plastic substrate is omitted, and a self-supporting film is used.

In 1984, Forward made the first detailed analysis of the use of a laser to propel a lightsail. His concept was to use a very large lens to reduce beam spread from a high-power laser, directing the laser light to a lightweight aluminum sail. He analyzed a flyby probe, a probe which decelerates in the target system, and a manned return mission [Forward 1984].

Both solar- and laser-pushed sails are good candidates for an interstellar probe propulsion system. As noted by Matloff [1984A], the limitation on the final velocity of a solar-sail is due to the heating of the sail. Mallove and Matloff [1989] calculate that a sail could achieve a maximum velocity of 0.012c after a close perihelion pass to the sun, if the material properties allow operation at the high temperatures produced by the close solar distance (700,000 km at closest pass) required. This velocity would, for example, allow a mission to Pluto with an outward flight time of a month. A mission to the Oort cloud at 1000 AU could be achieved with a flight time of only 2 years. Thus, while solar-pushed sails are not practical for propulsion for an interstellar probe, they are still of great interest for solar system exploration. The laser-pushed lightsail, or a laser augmentation to a solar sail, could also be useful for propulsion within the solar system.

Possible performance gains are:

Small spacecraft size. Prior to this work, proposals for high-performance laser-pushed lightsail propulsion envisioned sails of 10 square kilometer area. The initial analysis of improved performance sails indicates that the same delta-V can be achieved with a half square kilometer sail; the phase II work will confirm this number and look at ways of reducing this area by at least another order of magnitude.

High spacecraft acceleration. High spacecraft acceleration allows the same delta-V to be achieved over a shorter acceleration track, allowing smaller lens sizes and smaller sail areas. This requires a higher power density on target, and hence a sail with lower light absorption, higher thermal emittance, and higher temperature materials compared to the baseline.

Low required laser power. Since a major cost element of a laser propulsion system is the laser, a significant metric is reducing the power requirement. A lower power system also means that the transfer from research to operational system can occur earlier.

1.2. PROJECT

1.21 Dielectric Solar Sails

In 1989 I made an analysis of Forward's concept paper and identified several technical issues [Landis 1989]. None of the difficulties, however, make the project impossible per se, and many of the worst problems disappear if mission is a fly-by rather than a rendezvous.

Before the beginning of this study, I analyzed the concept of a small laser-pushed fly-by probe in more detail [Landis 1995], concentrating on the question of making the probe as small as possible. The most fundamental problem is that the Rayleigh diffraction criterion means that the minimum size of the probe is limited by the size of the aperture used to project the laser and the distance over which acceleration is achieved. The reduction of the physical size of the system by the improved technology moves it from the "far-future someday" regime into the realm of the possible.

Further improvements would be required, however, for an interstellar probe to become practical. The probe size is limited by the sail area, which can only be decreased by increasing the power density. Thus, a smaller and hence lower cost probe requires a material which can withstand a higher laser power density.

These improvements could be possible by using a sail made of dielectric film, instead of a metallic sheet. It is possible to choose refractory dielectrics, such as very thin films of zirconium dioxide or tantalum pentoxide, with excellent high-temperature properties, and also with very high emissivity and low absorption, which minimizes the heating. By making a “sandwich” of high index/low index dielectrics, it is possible to increase the reflectance at the laser wavelength to nearly unity, as pointed out by Forward [1986]. However, while the reflectance increases with the number of layers, the mass increases faster than the reflectance, and hence the optimum number of dielectric layers is one [Landis, 1991A]. For some missions, particularly in high power-density situations, dielectrics are indeed superior to metallic films.

Recently I completed a more complete optimization of dielectric films for laser-pushed sails, concluding that the optimum thickness was somewhat lower than the maximum-reflectance thickness of one-quarter wavelength [Landis 1998]. To date, this is the only detailed analysis of the use of dielectric films for solar sails.

Dielectric films are less effective for solar reflectance, since the thickness cannot be “tuned” to optimize reflectance at a single wavelength. This decreases the reflectance over the solar spectrum by roughly a factor of two. However, due to the low absorptance and high emissivity of candidate dielectric films, dielectrics are predicted to outperform metal films for high power densities; that is, for missions close to the sun. Trajectories which make a close pass to the sun, however, are extremely interesting for high delta-V solar-sail missions.

Since similar materials can be used for both solar and laser pushed light sails, both propulsion systems will be analyzed. The discussion so far has concentrated on use of laser-pushed dielectric sails for missions to interstellar velocities. For use of dielectric sails for high-velocity probes within the solar-system, a sail a few meters in diameter could be considered.

The serious difficulty of such sails is that, while the achievable acceleration can be very high, this is because the spacecraft mass itself is very low. For example, a five meter diameter, 50 nm thick sail of zirconium dioxide, with a density of 5.4 gr/cm^3, has a mass of only five grams. Structure (discussed below) might add an additional five grams of mass. To reach the performance potential of such a system, advances in miniaturization technology would have to reduce the spacecraft itself to comparable mass.

Could one imagine a spacecraft with a mass as low as five grams? I think that the answer is “yes”. The spacecraft would have to be built as a single chip of semiconductor. To enable this to be possible, the sail itself would have to act as an integral component of the spacecraft. For a power system, the sail would be used to focus light onto a miniature solar panel. Even at a solar reflectivity of 25%, a 5-meter sail would focus 4.4 watts onto the chip at Pluto. A 35% efficient solar converter on the chip--possible with today’s technology-- would result in 1.5 W of power at Pluto; plenty of power to run electronic systems. Likewise, the sail could be used as telescope mirror for imaging, and as the focusing lens for a diode-laser to communicate with Earth, by the use of an adaptive optical secondary to correct for the mirror shape.

1.22 Production Sequence

The film thickness of the dielectric reflectors discussed here, typically 25-200 nm, is extremely thin; considerably thinner, for example, than the film which makes up a soap bubble. These films are self-supporting against even relatively high accelerations because of their very low mass; the low mass is also what makes possible the high accelerations which allow high velocities to be achieved. The thin films can be made by vacuum evaporation of the dielectric material onto a removable substrate. However, if a payload is to be carried, additional structure is needed to couple the sail force to the payload.

One possible process sequence for fabricating a sail with such additional structure uses fabrication steps which are adapted from the semiconductor fabrication industry. The dielectric material is deposited onto a substrate with an interface separation layer. Different film types will be discussed; one separation layer which has been demonstrated in other applications is aluminum arsenide, used in the “peeled film” technology to make thin semiconductor layers. The film is then patterned with a photoresist covering all of the surface except for narrow openings, and an additional, thicker “rib” layer is deposited. Removal of the photoresist then also removes the deposited layer via the “lift-off” process commonly used in electronic fabrication, leaving the ribs as stiffeners. The rib material may be identical to the dielectric film, or could be a separate material chosen for tensile strength. Optionally, the material is then annealed to remove the residual stress of the deposition.

This forms a dielectric “tile”. Many tiles are then pieced together to form the sail. Note that the individual tiles could be extremely large; the architectural glass producers, for example, routinely deposits thin films onto sheets of glass as large as two-meters square, using thin-film deposition processes similar to those discussed.

The tile of dielectric is then mated to an open segment of a structural mesh, for example, an electroformed tantalum mesh. Such electroformed mesh is produced in industrial quantities from Buckbee-Mears Corporation. Once mated to the mesh, the dielectric film can be freed by dissolving the interface layer.

Since the majority of the area is the original thin dielectric material, the additional structure added is extremely light. Even at a light intensity of 1,000 times solar, the structural material added needs only to transfer a force of 3.5 millinewtons per square meter, and hence can be extremely thin.

For larger areas, process sequences can be envisioned to produce thin films on a continuous, roll-to-roll production process, as opposed to the individual tile approach discussed here.

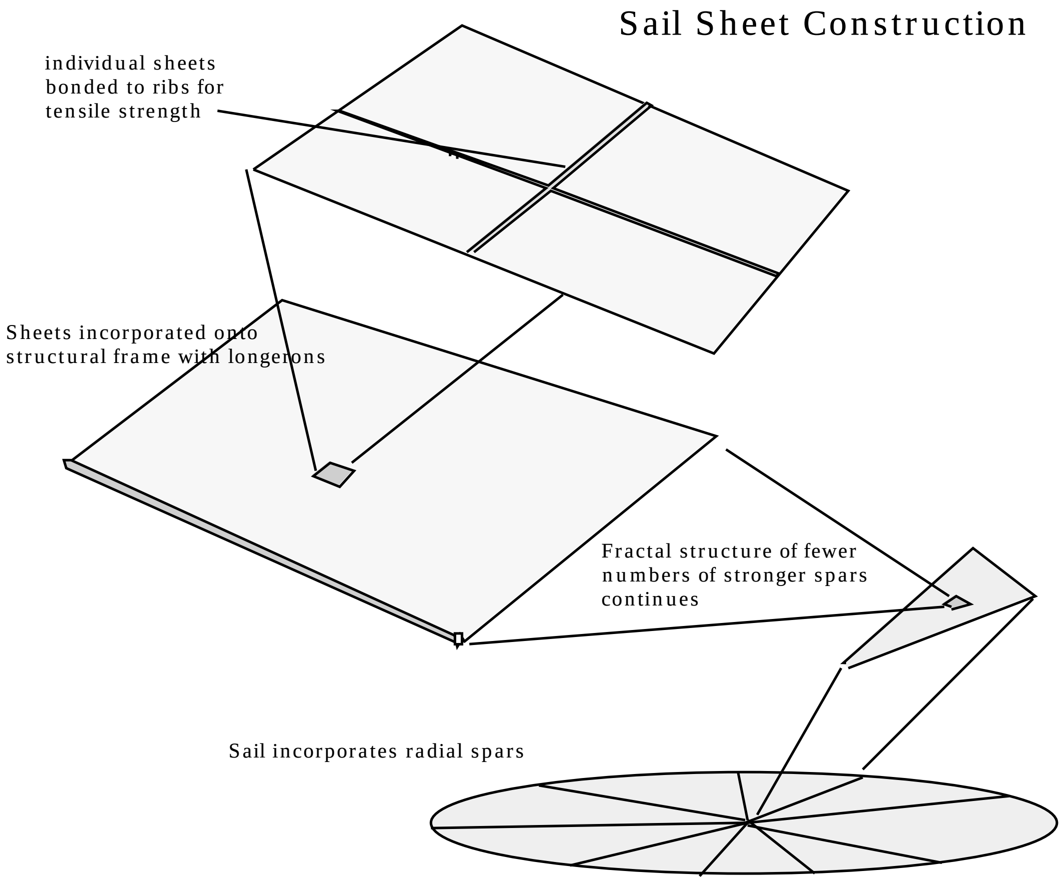

Figure 3

Structural concept for an unsupported film lightsail.

1.23 Baseline Mission Definition

In order to analyze the performance of various candidate sail concepts and materials, it was necessary to define the baseline missions which the propulsion system is to be designed for, and to analyze the performance of various candidate concepts when applied to these missions. Although there are a wide variety of possible missions to which the technology might be applied, ranging from fast probes to the asteroids to outer planet and interstellar missions, because of the short duration of this study it was decided to chose only two missions to analyze.

To define the baseline missions, I used data from the splinter group on beamed energy propulsion at the recent Workshop on Robotic Interstellar Exploration [Landis 1998A]. The splinter group defined four "strawman" missions, in order of distance were Nanospacecraft Solar System Missions (1-40 AU), missions to the Kuiper Belt Mission (100 AU), missions to the Oort Cloud (10,000 AU), and the Interstellar Flyby Mission (4.2 LY). As a baseline mission for this project, I chose the interstellar flyby using nanospacecraft.

Baseline Mission: Interstellar Fly-by

This mission requires the propulsion system to enable a fly-by mission to reach the nearest star, Alpha Centauri, in no more than 44 years, including the acceleration time. This requires roughly a thousand-fold improvement in performance over the best chemical propulsion systems built to date. Requirements for this mission are a peak velocity v of 30,000 km/sec (10% of c).

A lens is required to keep the beam spread due to diffraction at the aperture low. The fundamental diffraction-limit to beam spread is

$$\Delta y \geq 2.44\, \lambda\, s/a \quad (1)$$

where λ is the laser wavelength, a the effective laser aperture and s the distance. (The laser spot actually has an exponential tail outside this distance, but 84% of the light falls within the limit listed). To minimize the beam spread, a large lens is used. The effective aperture is then equal to the lens size rather than the physical size of the laser. Forward proposed that extremely large lenses (thousands of kilometers) can be made using the "paralens" concept; alternating rings of thin material with refractive index n alternating with empty space to form a very large fresnel zone plate.

For the flyby mission, the parameters chosen by Forward [1984] for the 20-nm aluminum sail are:

Laser power: 65 GW at 1000nm wavelength, vehicle vehicle mass 1 ton (1/3 payload), thermally limited acceleration 0.036 g, sail diameter 3.6 km, maximum velocity 0.11 c at 0.17 light years from laser.

1.24 Results for Beryllium Sail

In a paper presented at the 1995 IAF Congress [Landis 1995], beryllium was identified as a candidate material for a laser pushed sail with the potential for considerably better performance than the baseline aluminum sail proposed by Forward [1984]. The improved performance is due to the higher melt temperature and lower density of beryllium than aluminum. It was intended that this beryllium sail would be used as a baseline for comparison, since as of the beginning of the study, it was the best sail material identified. Therefore, a part of the study was devoted to re-examining the beryllium sail, using more exact values of the optical parameters.

Unfortunately, the recalculation using more detailed parameters showed that the performance of beryllium as a sail material was not as good as originally suggested. This was due to the original assumption that the ratio of optical absorption α to thermal emissivity ε for beryllium was the same as the α/ε ratio for aluminum. A literature search for optical properties of beryllium, however, showed that this assumption was in error. In fact, the optical reflectance is 0.54 for high purity Be (absorption 0.46), while the thermal reflectivity for the temperature range of interest is extremely high, on the order 0.98 (thermal emissivity ε 0.02). While these numbers are calculated for optically thick beryllium, and will change for thin films, the α/ε ratio should stay constant. An α/ε ratio on the order of 23 reduces the thermally-limited acceleration of the beryllium sail by a factor of 23 compared to the assumed α/ε ratio of 1.

Other high performance sail materials identified in the 1995 paper, scandium and niobium, were not reevaluated due to lack of time.

Therefore, the original Al sail proposed by Forward will be used in this study as the baseline case.

1.25 Reflectivity of Dielectric Sail Materials

Reflectivity is maximum when the thickness of the film is one quarter the wavelength of the light measured inside the film, when the reflected light from the front and rear of the film interfere constructively:

$$t = \lambda/(4n) \quad (2)$$

where n is the index of refraction. The higher the refractive index, the thinner the film can be to provide maximum reflectivity. The reflectivity of a quarter-wave single-layer thin film of a dielectric in vacuum is:

$$R = [(n^2 -1)/(n^2 +1)]^2 \qquad (3)$$

1.26 Properties of Dielectric Sail Materials

The amount of power that can be radiated by the sail is proportional to the maximum temperature (Tm) raised to the fourth power. Assuming that the absorption and the emissivity are fixed, this sets the thermal limit on the amount of laser power per unit area that can be focused on the sail, and hence sets the maximum force per unit sail area that can be achieved. The maximum acceleration which can be achieved is equal to the maximum force per unit area divided by the sail mass per unit area, which is equal to the mass density (ρ) times the thickness. Hence, if we compare sails of equal thickness, the figure of merit for acceleration of the sail, Z, will be equal to the produce of the fourth power of the maximum temperature divided by the density:

$$Z = Tm^4/\rho \qquad (4)$$

The maximum temperature Tm and the density ρ are thus the critical parameters to selecting the sail material. (Note that for a more detailed calculation, the reflectivity, emissivity, and absorptivity are also critical).

Several representative refractory dielectric materials were investigated. Table 1 shows the maximum temperature and density for some dielectric materials. Refractory oxides are among the easiest materials to deposit, and there is a wide body of experience in depositing optical coatings of with the low absorption figures needed for optical coating applications. Silicon dioxide is particularly well characterized, and has a high emissivity. Aluminum trioxide (alumina, or "sapphire") is also well characterized, and has a somewhat higher refractive index and a considerably higher melting point, resulting in higher performance as a sail material.

A higher refractive index can be achieved with tantalum pentoxide ("tantala") or zirconium dioxide ("zirconia"). The calculated reflectivity of quarter-wavelength films of some of the candidate materials are given in table 2. Both of these are used for optical layers. The higher refractive index means that the films have higher reflectivity, and also that the quarter wavelength criterion can be met with a thinner (and hence lower mass) film. Zirconia in particular is a highly refractory material, and shows the best figure of merit of any of the materials studied.

A higher refractive index, and hence higher reflectivity, can be achieved with semiconductors. Semiconductors, however, have the disadvantage of absorbing strongly at wavelengths shorter than their bandgap energy wavelength. Silicon, for example, although with the highest reflectivity of any of the materials (see table 2), can only be used with an infrared laser of wavelength longer than 1100 nanometers.

Finally, fluorides such as LiF, although materials with low index and comparatively low maximum temperature, have low absorption all the way up to far ultraviolet wavelengths. This will be a crucial property if ultraviolet lasers can be developed at the power levels and efficiencies required; by moving to a much shorter wavelength, the size of the lenses and sails can be proportionately reduced, allowing considerably better performance. Due to the low refractive index, though, the reflectivity is extremely low (see table 2). Since at the moment the best prospects for lasers operate in the visible and near-IR ranges and not in the UV, the fluoride materials were noted as interesting future prospects but not investigated further.

Although zirconia has the best figure of merit of the materials cataloged here, I was unable to obtain thermal emissivity data in the short period of the study. Since I was able to obtain data for sapphire, the sapphire sail material was used for the example calculation in the next section.

Table 1:

Physical Properties of Representative Refractory Dielectric Materials

"Maximum temperature" is defined as the melting temperature of the material except for diamond(where the maximum temperature is the temperature at which graphite conversion occurs), and silicon carbide and zinc sulfide (which sublime rather than melt). Figure of merit Z is compared to aluminum, with density of 2.7 and melt temperature of 940K.

Material	Max Temp. (°C)	Density (gr/cm^3)	Z (referenced to Al)
Oxides			
Silicon dioxide	1600	2.7	8.4
Alumina (Al_2O_3)	2327	3.96	25.6
Tantalum Pentoxide	1870	8.75	4.8
Zirconium dioxide	2715	5.5	34.2
Semiconductors			
Diamond	1800	3.5	10.4
Silicon*	1410	2.4	5.7
Silicon Carbide	2000	3.17	17.5
Zinc sulfide	450	3.9	0.36
Fluorides			
Lithium fluoride	820	2.6	0.60

*(absorbs below 1200 nm)

Table 2:
Reflectivity of Representative Refractory Dielectric Materials
Assumes a quarter wavelength film (maximum reflectivity)

Material	Reflectivity
Oxides	
Alumina (Al_2O_3)	26%
Tantalum Pentoxide	52%
Zirconium dioxide	42%
Semiconductors	
Diamond	50%
Silicon	75%
Silicon Carbide	56%
Zinc sulfide	48%
Fluorides	
Lithium fluoride	13%

1.27 Example Calculation:

The example calculation is done for an Al_2O_3 ("sapphire") sail. The example case is done for 400 nm wavelength laser light. At this wavelength, the quarter-wave thickness (for refractive index n= 1.765) is t= 57 nm.

At this sail thickness, given the density (ρ = 3960 kg/m^3), the sail mass per unit area is m/A= 226 kg/km^2. At this mass, the acceleration per unit power is: 0.03 m/sec^2 per (GW/km^2).

I examined reflectance and transmission data for a 0.5 mm thick alumina sample. This is considerably thicker than the sail thickness, however, it is still optically transparent in the visible range, and in the thermal range, the emissivity for a sail will at worst be under-estimated. So the α/ε ratio determined from this data is conservative.

Unfortunately, to the measurement accuracy, there was no detectable absorption. This is a desirable result, since absorption is the effect that causes the sail to heat up.

Emissivity varied with wavelength; essentially zero at wavelengths shorter than 10 micrometers, and averaging about 0.8 at longer wavelengths. This means that the effective emissivity, which is an integral of the emissivity over the thermal spectrum, will be about 0.8 at low temperatures, decreasing as the temperature increases, and will decrease rapidly at peak output wavelengths below 10 micrometers. At the operating temperature, most of the emission is at wavelengths below 10 micrometers, and the integrated emissivity decreases to about 0.1. Assuming, conservatively, an absorption of 0.5% instead of the undetectable absorption measured, the α/ε is 0.01.

For the calculated performance, the operating temperature was limited to 2/3 of the melt temperature Tm (1563 K). This ratio of operating temperature to melt temperature the same assumption that Robert Forward used in his baseline paper on laser-pushed lightsails [Forward 1984]. For a value of α/ε = 0.01, the incident power at Tm is 34 MW/m^2 , or 34,000 GW/km^2

At this thermally limited power density, the acceleration is 1000 m/sec^2, or one hundred times the acceleration of gravity..

This acceleration is for a bare sail, with no structure or payload. If we use the same assumptions for structure and payload used by Forward [1984], that the structure and payload together are 1.3 times the mass of the sail, this acceleration decreases to 43.4 G. At this acceleration, the sail reaches the cruise velocity of 10% of the speed of light in about 8.5 days.

This compares to Forward thermally-limited aluminum lightsail acceleration of 0.036 G, or a factor of 1200 times better acceleration. The higher acceleration is due to two factors, first the higher power density allowed by the high operating temperature of the films, and second due to the high emissivity/absorptivity ratio of the sail

The sail of 1200 times smaller size means that the sail diameter, if the lens size is kept constant, can be reduced by a factor of 1200, or conversely, if the sail is kept constant, the lens size can be reduced by a factor of 1200.

The minimum sail has 1200^2 times smaller area. The laser power, accounting for the lower sail reflectivity, required is 145 times lower. This means the interstellar fly-by mission can be accomplished at a power level of 448 MW (not 65 GW). The number accounts for the difference in thickness, density, reflectivity, and wavelength.

448 MW is about half the power output of a standard nuclear power plant. It makes the power requirement for the interstellar mission an amount that can be achieved in the reasonable future, and not an unreasonable amount which would require nearly a hundred dedicated electrical power plants.

1.28 Microwave/millimeter wave sail concept definition

Asecond task was to look at a concepts to use a thin mesh material pushed by a microwave or millimeter wave MASER rather than pushed by a laser. This task was done in collaboration with Dr. James Benford, of Microwave Sciences Incorporated.

The microwave/millimeter wave pushed sail is a similar concept to the laser-pushed dielectric film, in that it also uses a semi-transparent film pushed by a beam, but differs in terms of the wavelength. The physics of propulsion is the same; in particular, the force produced per unit of incident power is the same for laser and microwave concepts, 6.7 N/GW. However, the longer wavelengths require correspondingly larger apertures.

The microwave concept originally proposed by Forward [1985], was an interesting in terms of showing that the physics was possible, but was not practical. The proposed transmission aperture diameter of 50,000 km is four times the diameter of the Earth. While such a lens is not ruled out by the laws of physics, and could perhaps be constructed by a future civilization which has the ability to construct gossamer structures in deep space, it is beyond the realm of possibility for our existing technology. (Note that the transmission aperture consists of a thin wire mesh, and is not a solid object; nevertheless, a 50,000 km diameter structure made of wire mesh is beyond the capabilities of current technology).

However, this paper, although it appeared nearly 15 years ago, has not been examined critically or revised since publication. It appear that some of Forward's critical assumptions were rather conservative; conversely, it also appears that other critical assumptions in the study were optimistic. Clearly, a critical analysis and a new calculation using realistic assumptions was indicated. Several advantages of microwave beams indicate that it will be worth studying further:

1. Microwave production can be done with higher efficiency than laser beams, leading to lower cost of power and reduced waste heat.

2. Phased arrays of microwave transmitters are relatively easily done, while phased arrays of laser beams, although possible in principle, are difficult to achieve in practice

3. Large microwave apertures are much easier to fabricate than large laser apertures (consider the relative sizes of the largest microwave telescope, Aricebo, with the largest optical telescope, Keck.)

4. Microwave sails can be lighter than lightsails, since they can be perforated to reduce the weight. A crucial consideration was that a commercial vendor of perforated films that are of light enough weight to be used off the shelf for experimentation was identified (BMC corporation, of St. Paul, MN; web page http://www.bmcind.com/bmsp/in.htm).

Two assumptions of Forward were reasonable by the standards of 1985, but now technologically obsolete:

1. He assumed a wavelength of 3 cm (corresponding to 10 GHz frequency), in the microwave regime. Millimeter wave generation technologies now make it possible to generate wavelengths as low as 0.1 cm with relatively high efficiency; for example, Benford and Dickinson proposed power beaming at 245 GHz (0.12 cm), and detailed model of millimeter-wave beams for space power beaming has been analyzed by James Benford [Benford and Dickinson 1997]. This is an improvement of a factor of 25. Modest improvements in millimeter wave generation technologies make it a reasonable assumption that wavelengths lower than 0.1 cm can be produced with relatively high efficiency.

2. He assumed a sail of aluminum. Amore advanced material will yield considerably higher performance.

On detailed analysis of the Forward 1985 paper, it was realized that the Forward paper assumed that the mesh sail could be made superconducting, and would therefore absorb no microwave power. This assumption is unrealistic. At the power densities required, even very small parasitic absorption of microwaves would result in heating levels high enough that even a high-temperature superconductor would not remain superconducting (much less the aluminum assumed by Forward, which will transition to resistive at between 1.7 and 3 K). Furthermore, the very sparse meshes would have a induced current due to the microwave that is higher than the critical current of the superconductor, and therefore would lose superconductivity. I revised the analysis using an assumption that the mesh was not superconducting.

Under these assumptions, the sail absorbs a portion of the microwaves. For sail surface resistivity greater than 377 ohms per square, the absorbed power is higher than the reflected power. This reduces the effectivity of the sail by a factor of two. For sail resistivity that is large compared to 377 ohms per square, the reflected power is very low, and the sails are partially transparent to the microwave beam.

Astudy in more detail indicated that carbon (graphite) is the most preferable material for a microwave sail, under the assumption that the sail is not superconducting. By a fortunate coincidence, carbon sails are being developed by Dr. Knowles of Energy Science Laboratories in San Diego, independently of NIAC.

Asummary of the basic study of microwave-pushed sails was presented at the Advanced Space Propulsion Workshop in Huntsville in April. This presentation is included as Appendix 1 of this report.

Preliminary study indicates that an experimental demonstration of microwave/millimeter wave launch might be accomplished with a comparatively modest budget which would propel a lightweight sail at an acceleration of 20 m/sec^2 (that is, an effective net acceleration of one gravity upwards). This was investigated under a subcontract to Microwave Sciences Incorporated. Their report is given in Appendix 2.

1.29 Other Items Studied

Two additional areas were studied. In order to design a small experiment, it was necessary to see whether a sail concept could be developed that would be self-stabilizing in a microwave or laser beam. Concepts developed in this study are given in Appendix 3 (and also in parts of the microwave sail presentation, appendix 1).

In order to minimize the energy use, one concept is to recycle photons by use of a stationary mirror. This is discussed briefly in Appendix 4.

1.3 CONCLUSIONS

⦿ **Dielectric sails turn interstellar fly-by missions from science-fiction to technology**
⦿ **near-term laser-pushed sails** will allow outer-planet and Kuiper-belt missions in months or years, not decades
⦿ **farther-term laser-pushed sails** will allow interstellar flyby missions with mission times of decades, not centuries

⦿ **Millimeter-wave technology has been identified that may allow high-acceleration demonstration sails using existing equipment**
⦿ wavelength is too high for fast interstellar mission, but possibility of asteroid mission with travel time of few weeks
⦿ provides a possible stepping stone to beamed-sail technology

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Appendix 1

Presentation to 10th Advanced Propulsion Workshop, Huntsville, Al, April 5-8, 1999

Microwave-pushed Sails for Interstellar Travel

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University Space Research Association, Atlanta, GA

OAI Ohio Aerospace Institute

Ohio Aerospace Institute: Leveraging Resources Through Collaboration

The Microwave-pushed sail

The microwave-pushed sail is a alternative to a lightsail. Rather than pushed by light pressure, the pressure comes from microwave photons.

The concept of a microwave pushed sail was first published by Forward in 1985, elaborating on unpublished work by Dyson. Forward noted that proposals for solar power satellites involved microwave beams at levels of gigawatts, and suggested that if such solar power satellites were built, that the beam from the satellite could also be "borrowed" as a power source to accelerate an extremely small probe to a nearby star.

Reference: R.L. Forward, "Starwisp: An Ultra-Light Interstellar Probe," *J. Spacecraft, Vol. 22,* No. 3, May-June 1985, 345-350

Microwave pushed sails:

Advantages and Disadvantages

Disadvantage

1. Large sizes.

Microwaves have wavelength four orders of magnitude longer than that of visible light. A microwave sail propulsion system must have a diameter 10,000 times larger than that pushed by an optical sail to put the same power on the same sized target at the same distance.
(Forward's original proposed sail required a lens of diameter 50,000 km)

Microwave pushed sails:

Advantages and Disadvantages

Advantages

1. High efficiency.

Microwaves generation has much higher efficiency than laser beams, leading to lower cost of power and reduced waste heat.

2. Phased arrays.

Microwave phased-arrays (e.g., phased array radars) are an off-the-shelf technology.

3. Large apertures.

Large microwave apertures (e.g., Aricebo) are much easier to fabricate than large laser apertures.

4. Lightweight mesh sails.

Microwave sails need not be a solid film, but can be perforated as long as the hole size $<<\lambda$

5. Millimeter wave technology.

100 GHz technology now makes possible wavelengths of 0.1 cm with relatively high generation efficiency (33x smaller apertures than 3 GHz assumed in earlier study)

Microwave pushed sails:

Final Advantage:

Technology is Here Today

a demonstration of a microwave-pushed sail could be done with technology that is available in the laboratory.

Example Case

“Starwisp” mesh for interstellar fly-by mission

Sail

Aluminum wire mesh

- wire diameter = 0.1 micron
- wire spacing = 3 mm
- mesh fill-fraction = 0.067%

reflectance (assuming zero resistivity) = 50%

Sail diameter (fills beam at 4.5 AU) = 1 km

Sail mass 20 grams

Lens

wire mesh lens

diameter 50,000 km

Microwave source

10 GW

Reference: R.L. Forward, “Starwisp: An Ultra-Light Interstellar Probe,” *J. Spacecraft, Vol. 22,* No. 3, May-June 85.

Example Case

“Starwisp” interstellar fly-by mission

Performance

Acceleration 115g

D_{cutoff} : 6.8 10^{11} m (4.5 AU)

Acceleration time to cut-off: 10 hrs

Sail velocity at cutoff: 1/10 c (30,000 km/sec)

Microwave power density on sail: 8.6 kW/m^2 (6 times solar intensity)

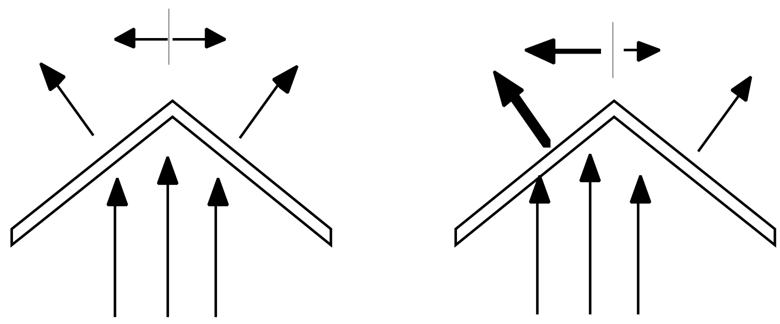
Sail velocity at end of acceleration: c/5

(reaches Neptune in roughly a day)

D_{cutoff} defined as the distance at which beamspread becomes greater than sail diameter

Stability of a Test Microwave sail

Lateral translation stability can be achieved if the test sail is made
concave toward the source

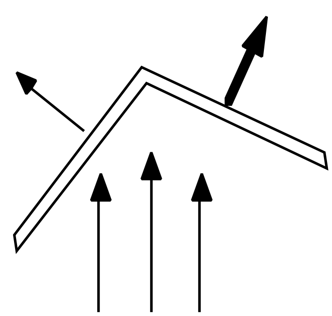


sail centered in beam
no net sideways force

sail off beam center
net sideways force tends to restore sail

Net force is outward: sail is kept in tension

Rotational (pitch and yaw) stability **cannot** be achieved
--Unstable for the case of a test sail concave toward the source



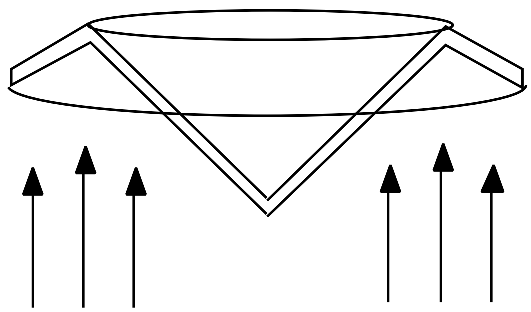
Sail rotated in beam results in torque that tends to increase rotation angle

--Stable for the case of a test sail convex toward the source, but net inward force tends to collapse the sail

Solution: sail must be rotated

Stability of a Test Microwave sail

Rotational and translational stability **can** achieved if an annular beam is chosen



Sail shape designed for stability in annular beam

center section stabilizes sail against translation

outer ring stabilizes sail against rotation

outer ring maintains outward tension

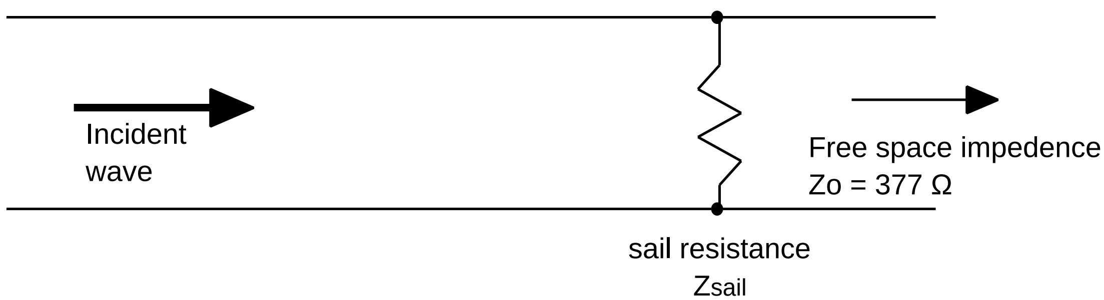
1985 analysis assumed
sub-micron wires of superconducting aluminum

- **Bulk Al superconductor transition temperature 1.2 K**
- **thin films of Al show superconductivity as high as 3.7 K**
- **other metals have higher transition temperatures**

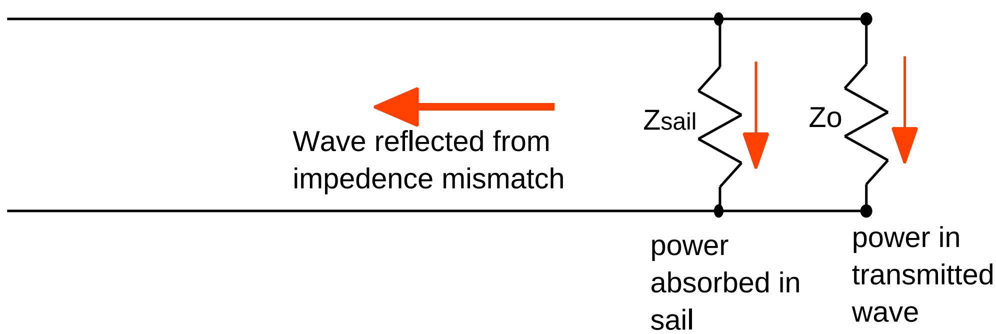
Unlikely that this temperature could be achieved, due to heating by sunlight, starlight, microwave absorption, cosmic microwave background, IR radiation from galactic dust, friction with interstellar gas, etc. (starlight alone will raise equilibrium temperature to >12K)
This was noted as a problem in the 1985 paper.

Analysis needed:
Can the mission be done with a non-superconducting sail?

Transmission-line model of microwave reflectivity from sail



The incident wave encounters an impedance mismatch at the sail. The sail resistance Z_{sail} is in parallel with the free-space impedance Zo of 377 Ω.



The output wave consists of three parts: reflected wave, power absorbed in the sail, and transmitted wave (modeled as power absorbed in 377Ω Zo resistor)

Effective impedance:

$$\frac{1}{z_{effective}} = \frac{1}{z_o} + \frac{1}{z_{sail}}$$

Reflectance coefficient at impedance mismatch:

$$\Gamma = \frac{\left[\frac{Z_{effective}}{Z_O} - 1\right]}{\left[\frac{Z_{effective}}{Z_O} + 1\right]}$$

Reference: Adler, Chu and Fano, *Electromagnetic Energy Transmission and Radiation*, 1960, page 90.

power reflected:

$$P_{reflected} = \Gamma^2$$

Power shared between absorbed and transmitted waves

Absorbed power

$$P_{absorbed} = \left(1 - \Gamma^2\right)\left[\frac{1/Z_{sail}}{1/Z_{effective}}\right]$$

Transmitted power

$$P_{transmitted} = \left(1 - \Gamma^2\right)\left[\frac{1/Z_O}{1/Z_{effective}}\right]$$

Force:

$$F = 2P_{reflected}/c + P_{absorbed}/c$$

Approximations

- assume that the holes in mesh are << wavelength; therefore, the mesh can be treated as a continuous sheet
- Rectangular mesh, polarization vector in direction of (one of) the wires
- Assume bulk value of conductivity

Sheet resistance can be calculated by summing resistance per unit length of individual wires

Z_{sail} = (resistance/meter)/(wires/meter)

$$Z_{sail} = \rho/AN$$

where:

ρ is resistivity (Ω-meter)

A is cross sectional area per wire (m^2)

N is wires/meter

Conductivity of small-diameter wires

- theory says that wires should behave like bulk material only if the size is much larger than the average scattering length
- Scattering length in metals is on the order of 50 nm
- 100 nm wires are at the limit of the bulk conductivity range of validity

■ Theory says scattering from surface should **increase** resistance for wires of diameter comparable to scattering length

■ Experiments on thin films shows increase in resistance higher than calculated:

65 nm aluminum films

Rsheet calculated from bulk resistivity	0.40Ω
Rsheet with Sondheim/Fuchs correction	0.47Ω
Measured Rsheet	1.98Ω

■ Higher resistance probably indicates non-ideal film quality

reference: R.L. Cravey et al., paper AIAA 95-3741

Example calculation:

Non-superconducting Starwisp mesh

(neglecting diffraction loss)

Resistivity 28 nΩ-m = 29 10^{-9} Ω-m

$A = \pi (0.05\ 10^{-6})^2 = 7.85\ 10^{-15}$m

N = 1/(3 mm/wire) = 333 wires/meter

$Z_{sail} = \rho/AN$ = 11,000 Ω/square

Of the incident wave power:

reflected: 0.03%

absorbed: 3.4%

transmitted 96.6%

Conclusion: sparse meshes absorb, rather than reflect, microwaves

(Needs 29 times higher power to reach same performance as 50% reflective superconducting sail)

Question for future study:

can the microwave reflectivity be improved by making a mesh is of resonant dipole elements?

Resistive meshes are Thermally Limited

the maximum acceleration that can be sustained is limited by the radiative cooling of the mesh

Radiated power per unit area

$P/A = 2\ \varepsilon\sigma\ T^4$ for a plane sheet

$P/A = 4\ \varepsilon\sigma\ T^4$ for a sparse mesh

radiative cooling is isotropic-- no net thrust if the mesh is equally "black" in both directions.

If mesh is black on transmitter ("rear") side but reflective on space ("forward") side, thermal radiation contributes another 50% thrust, but maximum power absorbed decreases by factor of 2. Result is net loss in acceleration but a gain in energy efficiency.

Figure of Merit for an absorbing mesh

For a purely absorbing mesh,

$a = P/mc$

$= P/\rho fAtc$

so for thermally limited performance:

$$a = 4\ \varepsilon\sigma T^4/f\rho ct$$

- Single most critical parameter is **high operating temperature**
- real mesh will be both reflecting and absorbing

ε thermal emissivity

σ Stefan-Boltzmann constant

T maximum allowable operating temperature

c speed of light

f the mess fill fraction (metal area/total area)

ρ density of material

t effective thickness

Example case: thermally limited Graphite sail

- Thickness 200 nm (1000 nm graphite sheets currently available)
- 2333 K operating temperature (2/3 of 3500K sublimation temp)
- emissivity 0.5 (assumes slight decrease due to thinness of sheet)

thermally limited performance is

24.4 m/sec^2 (2.5 g)

- only 1/50 as good as the (non-thermally limited) performance of the superconducting mesh
- 24 m/sec^2 is still **impressive** performance
  - 20 hour acceleration, then coast to Pluto in three weeks
  - 1/100 speed of light in $1^1/_2$ days
  - 1/10 speed of light in 2 weeks

- assume mesh fill fraction 0.2% (200 nm wires, 5 wires/ mm)
  - very conservative compared to Starwisp study
  - absorption is 11%
  - reflection <0.5%
- Sail mass (2300 kg/m^3)(200 10^{-9} m) (0.002)
  - 0.92 mg/m^2
  - 92 kg/km^2
  - add 80 gram distributed payload and avionics (reduces acceleration to 22.5 m/sec^2)

Probe mass is 1 kg for 100 meter square sail

- thrust is 22.5 N

❑ **56 GW** of microwave power needed

(measured at the sail)

Example case: thermally limited Graphite sail

- assume maximum velocity 1% of c
  - great performance for Kuiper or Oort mission
  - would take over 400 years to reach nearest star

- Large lens still needed
  - requires 50 million kilometers to reach 1/200 c
  - requires 125 km diameter microwave lens (at 100 GHz)

- **modest performance compared to Starwisp, but**
- **(slightly) more reasonable parameters**

Superconducting mesh

possible solution: use high temperature superconductors

- **YBCO superconductors can be deposited in thin films**
- **Transition temperatures over 77 K can be achieved in deep space**

note:

- **YBCO is brittle, may need copper substrate to deposit on**
- **technology development needed to make thin meshes**

Analysis needed:
(1) what is maximum microwave power achievable before induced current exceeds critical current?
(2) Parasitic absorption of microwave power by non-superconducting portions may heat sail; this must be accounted for.

Analysis needed:

Can the mission be done with a HT-superconducting sail?

Conclusions

microwave-pushed meshes are a possible propulsion technology for interstellar (or other high ΔV) missions that may be demonstrated with technology available in the near term

- **non-superconductive meshes do not perform as well as superconductors**
- **absorption in non-superconductors puts thermal limit to performance**
- **graphite sail has thermally-limited performance >10 better than any other material**
- **performance still beats all other existing technology**
- **payload mass is very small for reasonable power levels**

❒ trade-off: can high-temperature superconductor meshes be made? Can they be kept superconducting in use?

Appendix 2

Report of Microwave Sciences Inc. subcontract
Feasibility of a high-power microwave-pushed sail experiment

FINAL REPORT

LABORATORY DEMONSTRATION OF MICROWAVE BEAMED POWER PROPULSION

For
Ohio Aerospace Institute
SRA program
22800 Cedar Point Road
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Purchase Order Number 4762
Project Number R-700-200258-30025
Technical Point-of-Contact: Dr. Geoffrey Landis

May 1999

Microwave Sciences, Inc.

LABORATORY DEMONSTRATION OF MICROWAVE BEAMED POWER PROPULSION

1] Goals and Key Features

Beamed Power electromagnetic radiation-propelled ultralight foils, films or sails have been proposed for many space missions. For example, the beamed power sail system concept has recently been evaluated by JPL as a candidate for the Interstellar Precursor Mission. Of all the propulsion concepts explored, beamed energy clearly works, i. e., needs no new physics, and has the most potential for near-term development. In particular, the technique of using directed beams of coherent radiation to propel a sail has substantial advantages over rockets in that no fuel at the spacecraft is required. Indeed, as has been pointed out by independent studies at JPL and the U.S. Air Force, this is the only method for interstellar propulsion that uses known physics and whose elements are being developed for other purposes.

But as yet there is no laboratory demonstration and evaluation of the realities of the method. The physical principle is not in doubt, but the realities are not known. These realities, such as thermal effects, stability, and true energy efficiency will dominate the practical realization of the beamed microwave/laser sail system. We consider here how to change this situation fundamentally by conducting a laboratory exploration/demonstration of microwave beamed power propulsion. This will move 'photon-pushed' sails from paper concept to laboratory reality. The experiment sketched here will be conducted in a one-gee environment in vacuum in a laboratory, not in space. The sail will fly at high accelerations over meters of flightpath. The experiment will measure the significant physical parameters of EM-propelled flight: acceleration, velocity, efficiency, heating of the surface, the influence of incident radiation distribution on the foil and foil stability. It will demonstrate the technique as a practical candidate technology for advanced deep space and interstellar propulsion. And it will provide a testbed for further experiments on

- sail stabilization schemes
- flight of sails with payloads
- improved sail materials

2] Acceleration of Sails with Microwaves

Carbon [graphite] is an excellent material for sails because of its high temperature of sublimation. We describe here the theoretical basis for levitating and accelerating a thin film of carbon fiber in a laboratory vacuum chamber at several gees using microwave radiation pressure.

The microwaves are somewhat absorbed by the carbon fiber. Although this loses some of the possible thrust by absorbing, not reflecting, the power, there is great gain [by T4 dependence] in the ability of the material to handle the incident power without melting or sublimation. The acceleration a produced by a power on a film of mass m, area A, thickness t, and density ρ is

$$a.=.[\, 2\eta+\alpha-\tau]\ \ P/mc = [2\eta+\alpha]\ \ P/MA\ c$$

where η is the reflectivity of the film of transmissivity τ and absorptivity α , M is the mass per unit area (m = MA) and c is the speed of light. The transmissivity is assumed negligible on the right hand side because the carbon fiber sail material we will be using has little or no (~1%) transmissivity.

Of the power incident on the film a fraction αP will be absorbed. In steady state, [which will be achieved in ~10 ns for 1 μm thickness sail] this must be radiated away from both sides of the film with temperature T and emissivity ε by the Stefan-Boltzmann law

$\alpha P = 2A\ \varepsilon\ \sigma T^4$

where $\sigma = 5.67 \times 10^{-8}$ W/m2 K4 is the Stefan-Boltzmann constant. Eliminating P and A, the sail acceleration is

$a = [2\ \sigma/c]\ \{\ \varepsilon\ (2\eta+\alpha)\ /\alpha\ \}\ (T^4/M)$

where we have grouped constants and material radiative properties separately. Clearly the acceleration is temperature limited. If we assume typical values at room temperature, for example $\varepsilon=0.6$, $\alpha=0.1$, and evaluate, the acceleration is

$a = 2.27 \times 10^{-15}\ (2\eta+0.1)\ T^4/M$

In useful units this is

$a\ (m/s^2) = 36.3\ \ (2\eta+0.1)\ T(2000\ K)^4/M(g/m^2)$

For a totally absorbing, non-reflecting material, as carbon might be assumed to be, the $(2\eta+0.1)$ factor is 0.1. For the 7 g/m2 C-C material currently under development by Energy Science Laboratories, Inc. (ELSI) and recently measured at JPL with microwaves at 7 GHz, $\eta = 0.89$, so the factor is 1.88. [At first this seems somewhat surprising, but is likely due to a combination of resistivity and impedance-mismatch effects.] Therefore acceleration [or, alternately, the mass per unit area, or areal mass density] will be higher by this factor.

For the 7 g/m2 C-C material at 2000 K, we get 9.8 m/s2 and the sail levitates. Anything lighter will fly. These new ultralight carbon-carbon sail fabrics should allow acceleration at several gees. In this example the power density is ~1.1 kW/cm2. For the proposed 100 kW experiment this implies an area of ~90 cm2, which with shape factors means a diameter of ~10 cm. However, we intend to go well beyond levitation to achieve flight by lowering the mass density substantially. ELSI has already made sails of carbon/epoxy at 1 g/m2, and they feel they can make the C-C material substantially lighter than 1 g/m2. So these new ultralight carbon-carbon sail fabrics should allow acceleration at several gees.

Determining what temperature we can really operate at will be an important goal of the experiments. The carbon vapor pressure increases very rapidly with temperature. For example, at 2000 K the evaporation rate is 1μg in 21 days. The rate may be about 1μg in 20 seconds at 2500 K, so we shouldn't try to operate higher.

3] Sail handling for Vertical Support

Experiments with ultra-thin sails would benefit handling by wholly hands-off technology, using only magnetic fields. Managing the sail can employ magnetic fields for vertical support. This can enable study of sails in a cylindrical, vertical, vacuum chamber while simultaneously developing methods of handling which might apply in space.

Though the diamagnetic force is feeble, the lifting ability scales as B2. The force is (**M** o grad)**B**, where the magnetic moment **M**=(X/μ0)VB, and V is the volume and X the susceptibility. The gradient of B must lie along B to exert a force, so a dipolar field generated by a solenoid can support a diamagnetic material at the top against gravity. A strong magnetic field can vertically support diamagnetic sails if

B [Tesla] > 6.1 [(l/10 cm)(Xc/X)]1/2

where l is the field gradient and X is the sail's magnetic susceptibility in units of carbon's, Xc. Gradients of 10 cm in 6T fields are available in strong electromagnets. Generally any diamagnetic sail can float, but carbon may be preferred because it has the largest known ratio of X/ρ (susceptibility to mass density). [Paramagnetic materials are unstable.]

Allowing a sail to settle onto a static dipolar field lets it adjust in the gradient scale. Then it can be moved somewhat vertically with pressure from the microwave beam from below, allowing study of absorption, transmission and reflectance. The sail's temperature will rise and can be measured by observing its infrared emission. These can be compared with values for these quantities used in the full dynamic model.

Combined handling by static and dynamic fields will allow experiments that can be understood by eye, noting sail behavior in a variety of handling conditions. The sail can be "tossed," caught, heated and spun in a continuous, observable experiment.

(It may prove possible to even catch a sail at the top of its flight, by embedding it in another static field. The sail will slow in the static field. Then a pulsed field can catch it from below, trapped. Retrieval will allow study of the material without having the contamination of a hot sail stuck to the chamber walls.)

4] Experiment Description and Physical Layout

The following is a concept for developing an experimental basis for microwave-driven flight. It consists of two types of experiments, shown in Figures 1 and 2

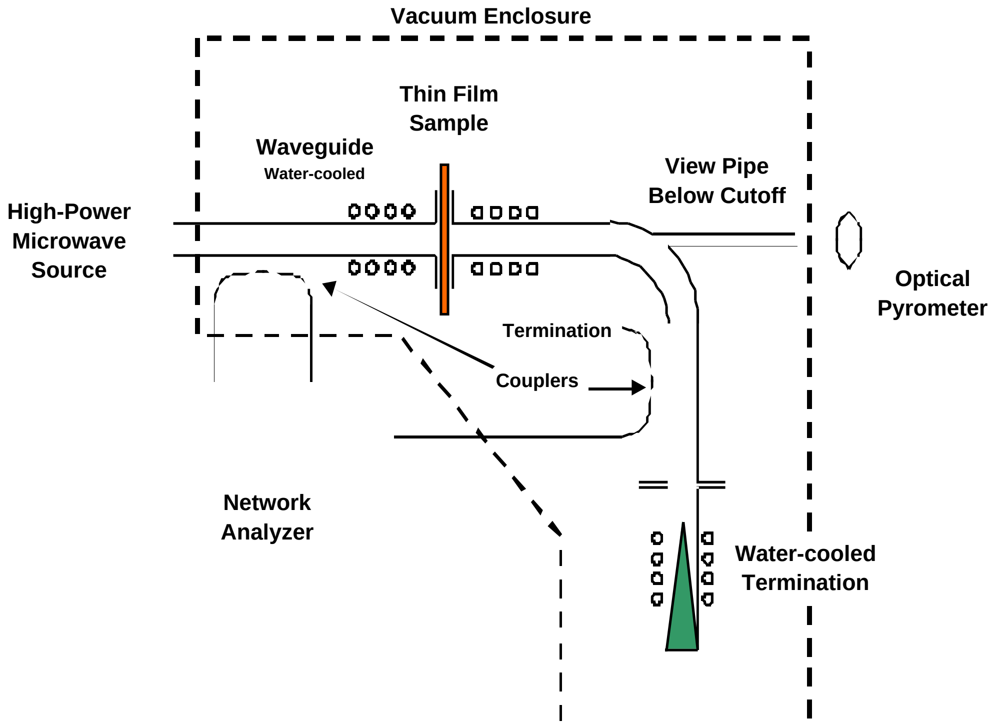

Figure 1. This experiment to measure the microwave properties of a thin film sample at high temperature confines the high power microwave energy inside waveguides.

Sail Microwave Property Measurements

We first measure material radiative properties (reflectivity, absorptivity, and transmissivity) of sail materials for a variety of thicknesses and at several microwave frequencies. The apparatus shown in Figure 1 will also heat the material with the microwaves and measure the properties at higher temperatures. This data can then be input to a predictive model for flight experiments.

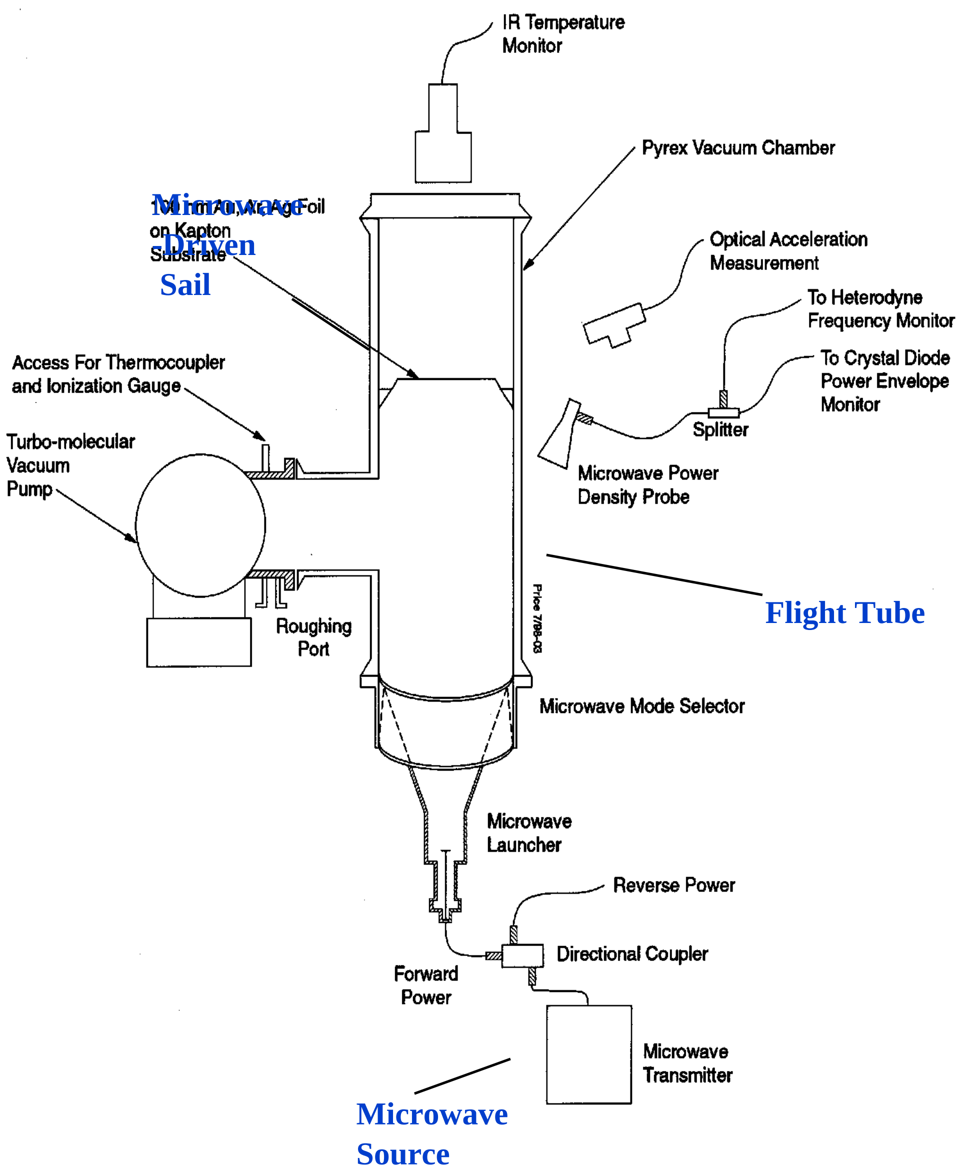

Figure 2. Concept for a microwave-driven sail experimental demonstration. Sail material is initially located in the chamber at the microwave injection point. Principal diagnostics are shown: sail motion is photographed, Doppler laser used to measure velocity; sail temperature is measured by pyrometer.

Sail Flight Experiments

A rough conceptual schematic for the chamber and the flight apparatus inside it are shown in Figure 2. We want to measure physical parameters while avoiding complex diagnostics when simple ones will do. A preliminary short list of key features to be measured:

o trajectory of the sail

o surface temperature of the foil vs. time
o velocity and acceleration of the foil (probably by optical photography) vs. time

Experiments begin with lower power of a few kW to produce levitation and low accelerations. The later experiments at 100 kW (at 95 GHz, see below) will reach high accelerations of several gees as lighter materials are fabricated. Later work will begin sail stability experiments.

For upward flight of a 1 g/m2 sail at 2000K we get 7 gees, 6 gees net. The experiments described are designed for powers up to 100 kW. The power density is 1089 W/cm2 so the sail area and diameter are about 90 cm2 and 10 cm [depending on the radial distribution of power].

Foil [grid] handling, set-up and launch techniques are especially important. Note we haven't included magnetic support (levitation) in the initial experiment because the C-C sail materials at ~1 g/m2 are self-supporting. Diamagnetic support can be added later. The mode extracted from the gyrotron and launched will be an attractive pattern, a Gaussian beam shape. There is a tradeoff of acceleration and the point where thrust falls off due to beam spread. We choose the launcher diameter to be ~ 10 cm, so beam spreading will begin at about z0= 0.1 D2/λ, about 33 cm downstream. Further on the beam begins to spread as z20/ z2 where z is the vertical direction.

Early tests will study a simple, flat sail. Stability and beam-riding will demand more complex designs, such as a sail with several different slopes varying with radius. The major effects on stability [spin, annular beam, or a suitable radial slope profile] can be separately tested in the same facility, after the basics of sail flight are initially explored.

5] The Gyrotron Microwave Source

The choice of microwave device for an experiment is determined by maintaining the highest power per unit area while keeping the diffraction distance, D2/λ, as great as possible to avoid beam spreading. The power must be continuous, not pulsed, power ['CW' power] so that the acceleration is maintained.

By these criteria the best type of device is the Gyrotron, which has been extensively developed for fusion plasma heating at high frequencies. Figure 3 shows a state-of-the-art 95 GHz, 100 kW Gyrotron now being built by CPI of California. The electricity –to–microwaves efficiency goal is 50%, though 40% is more realistic. Figure 4 shows a 110 GHz, 1 MW version; the devices are not large for their power.

Several institutions have such Gyrotrons. Therefore the experiment could be done at the Air Force Research Lab, General Atomic, Commonwealth Power Industries (CPI) or a University.

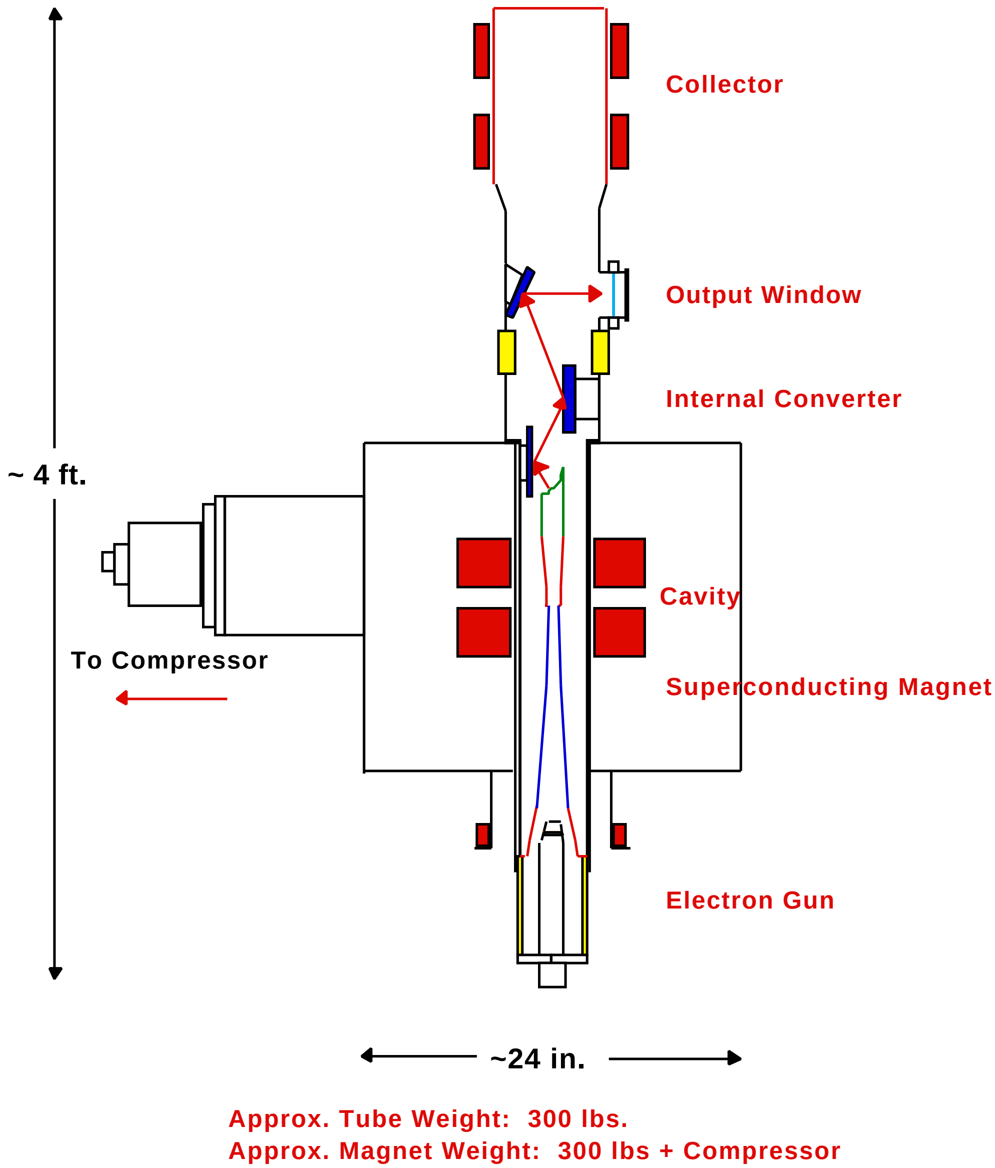

Figure 3. Schematic diagram of a 95 GHz, 100 kW Gyrotron

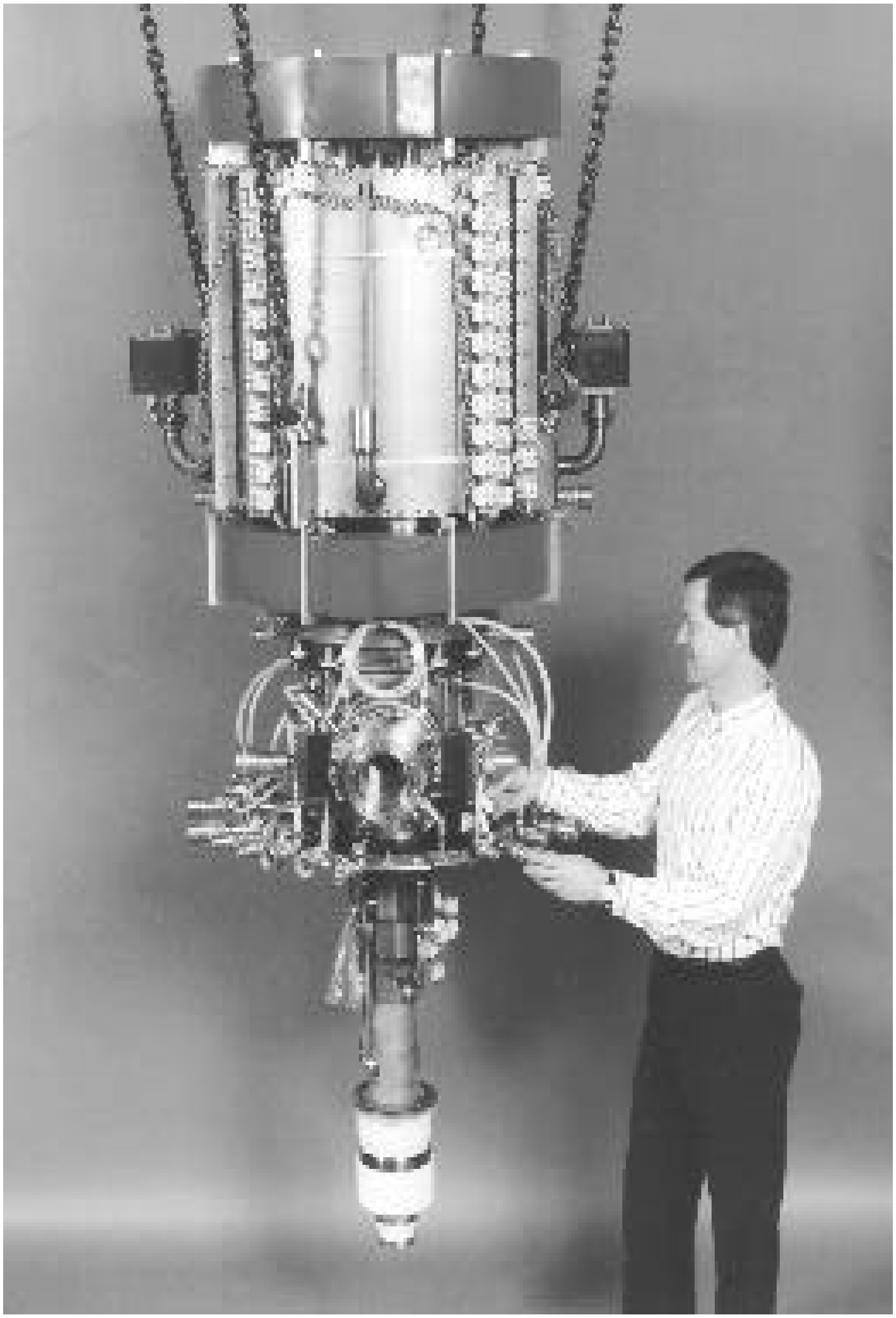

Figure 4. A 110 GHz, 1 MW Gyrotron made by CPI.

6] Performance of Baseline Experiment

For the above example [a 1 g/m^2 sail at 2000K, accelerated initially at 7 gees, 6 gees net], we calculate the trajectory of a 10 cm diameter sail. The initial acceleration produces a peak velocity at zo of about 6 m/s. The falloff of force above zo causes the sail to reach a peak altitude of about 3 meters. So this should be the vertical scale of the experiment. [Note that this is only a sizing argument; because we have assumed a sail temperature.]

7] Task Plan and Schedule

Task Descriptions

Task 1 Sail Microwave Property Measurements
Measure material radiative properties (reflectivity, absorptivity, and transmissivity) of sail materials over an order of magnitude in thickness and at several microwave frequencies. Also heat the material and measure properties at higher temperatures. This data goes to the Modeling sub-task for development of a predictive model for flight experiments.

Sub-Tasks:
- Sail Material Fabrication
- Laboratory Measurements
- Modeling

Task 2 Sail Flight Experiments
Consists of the experimental process: Electrical design, Mechanical design, Design reviews, Safety plan, and, finally, Experiments. The experiments begin in the chamber with lower power up to levitation and low accelerations. The later experiments will reach high accelerations of several gees.

Sub-Tasks:
- Advanced Sail Material Fabrication
- Laboratory Operations
- Modeling, Data Analysis and Comparison

Appendix 3

Analysis of Sail Stability for a Demonstration

The experimental test being proposed will be to accelerate a small sample of sail material (with n payload) by a laser or a microwave beam. For this test, the sail shape should be chosen (1) to keep the sail in the beam, (2) to keep the sail from rotating. Also, it would be desirable to use a sail with no structural support by compression members, and hence a third requirement is (3) to keep the sail from collapsing. Each of these desired effects can be achieved by suitable choice of sail shape, however, it is difficult to achieve all of these at once.

Keeping the sail in the beam is achieved if the sail shape is designed to correct small translational errors. This is accomplished if the sail shape is concave toward the beam source, for example, if the sail is a bowl shape, or a conical shape. In this case, as the sail moves away from the center of the beam, a restoring force pushes it back toward the center of the beam. This is shown in figure 1.

This shape of sail also is the shape which achieves the third goal, of keeping the sail from collapsing. The outward force due to the light pressure tends to “inflate” the sail, and hence puts it in tension.

However, this shape sail does not, in general, achieve the second goal, of restoring the sail attitude if it rotates. This is shown in figure 2. The force on a reflective sail is normal to the surface, regardless of the beam direction. However, the magnitude of the force is proportional to the cosine of the angle of the incident light from the sail normal. Thus, as the sail tilts, the force increases to increase the sail angle. This results in an unstable equilibrium: any disturbance in sail attitude will tend to be amplified.

There is no obvious solution to this dilemma in terms of the sail shape. An addition of a weight to move the center of gravity of the sail rearward would convert the unstable torque into a stable torque, but at the expense of collapsing the sail, since with no structural members in compression, the sail material will only accept tensile loads in the plane of the sail.

The solution proposed here is that the sail should be spun before the beam is applied. Spinning the sail will have several benefits

(1) torques due to nonuniformity of the sail will be averaged out

(2) gyroscopic stability will keep the sail attitude constant

and (3) the effective centrifugal force will tend to keep the sail flat

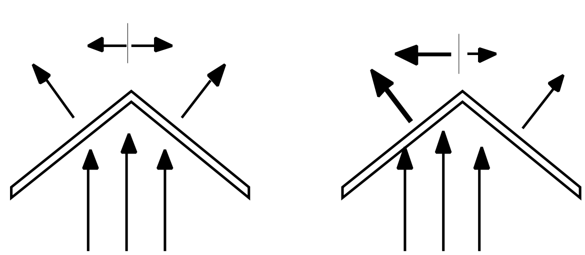

Figure 1. Self-centering of concave sail. (left) when the sail is centered in the beam, the side force on the left side of the sail and on the right side of the sail are equal, and there is no net force. (right)

when the sail is off-center in the beam, the side force is unequal, and the resultant force restores the sail to the center of the beam.

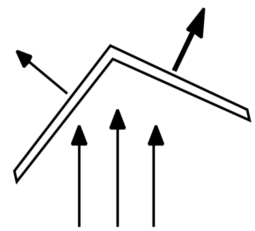

Figure 2. Attitude instability of concave sail. If the sail rotates, the force increases on the side which is closer to normal to the beam. This results in a torque which tends to increase the rotation. In the example shown, the force is greater on the right side of the sail, and the resultant force tends to torque the sail in a counterclockwise direction.

An alternate solution is for the sail to ride a beam that is not uniform. If the beam profile is chosen to be annular, with a minimum at the center and a maximum intensity at a fixed radius, then a sail shape can be chosen to be stable in both attitude and position in the beam, by use of a sail with a folded shape incorporating both concave and convex sections.

Appendix 4

Energy efficiency and photon recycling

I would like to acknowledge discussions with Dr. Robert Metzgar, Department of Electrical Engineering, Georgia Institute of Technology, for useful discussion of many points in this analysis, and for allowing to read a preprint of his article on photon recycling sails for Earth-Mars transportation in the *SFWA Bulletin* [Metzgar 1999].

A significant difficulty of lightsail concepts for propulsion is the problem of energy efficiency. A lightsail (or microwave sail) can be viewed as a rocket with infinite specific impulse. It is counterintuitive, but nevertheless true, that a rocket with infinite specific impulse is in fact very non optimum for propulsion in terms of energy efficiency.

Th*e ma*ss efficiency of a rocket is defined as the specific impulse: the amount of momentum you get per unit of reaction mass. This (with a factor of g) is proportional to the exhaust velocity. So, for the highest mass efficiency, you want to maximize the specific impulse. A lightsail therefore has the maximum possible mass efficiency, since it produces thrust with no use of (onboard) reaction mass. The specific impulse is infinite.

However, this is not true for the energy efficiency. If you have a fixed amount of energy, but can vary the reaction mass, what do you do to maximize the velocity (i.e., the momentum) achieved per unit energy? [For a concrete example, picture a nuclear reactor on your rocket that puts out a fixed power of P watts, all of which is transferred with perfect efficiency to the reaction mass. Is it most energy efficient to run a little hydrogen through the reactor, and exhaust it at great velocity, or to run a lot of hydrogen through, and exhaust it at modest velocity?]

To simplify the problem, consider the case where the rocket is stationary. In this case, the exhaust energy is $E = 1/2\,mv^2$, and the exhaust momentum is $p = mv$. So the momentum gained per unit of energy expended is $p/E = 2/v$, that is, the energy efficiency is *inversely* proportional to the specific impulse. The higher the specific impulse, the worse the energy efficiency, and for a system of infinite specific impulse, the momentum gained per unit of energy is zero.

This is not precisely correct for the case of a lightsail. The thrust of a laser sail is

$$F = 2E/c \qquad (1)$$

(where the factor of two accounts for the fact that the reflection means that twice the photon's momentum is transferred to the sail). The thrust per unit energy is thus:

$$F/E = 2/c \qquad (2)$$

(which corresponds to a thrust to energy ratio of 6.7 newtons per gigawatt.) Thus, in terms of the energy efficiency, the effective exhaust velocity is not infinite, but equal to c/2. Nevertheless, this represents an extremely low efficiency in terms of use of energy. Since c=300,000 km/sec, a rocket with exhaust velocity of c/2 has 30,000 times lower energy efficiency than a rocket with exhaust velocity of 5 km/sec.This is not precisely correct for the case of a non-stationary lightsail. If you define the energy efficiency in a different way, as the fraction of the laser energy transferred to the sail, [dE(sail)/dE(laser)], this goes to zero as the velocity goes to zero. The energy transferred to the sail per unit time is the power, which equals force times velocity. Ignoring the Doppler shift for the moment, the laser beam gives a constant force per unit of laser power, so the energy transferred to the sail per unit time is proportional to the velocity. Hence, energy efficiency is proportional to the velocity. This is exactly what you expect: since energy goes as V^2, dE/dV is proportional to V. (By this definition rockets also have zero energy efficiency when they're motionless.) From this you can calculate the optimum exhaust velocity of a rocket (i.e., the optimum specific impulse) if you wish to maximize the momentum per unit of energy. When you include the energy expended in bringing the reaction mass to speed, it is no longer the case that the optimum specific impulse is zero; this is only true for the case of a stationary rocket (or sail). For a non-stationary rocket, the optimum exhaust velocity turns out to be exactly equal to the rocket's velocity. Therefore, it is clear that for low velocity missions, such as planetary missions, the optimum use of energy is to use a rocket; for high velocity missions, such as the outer planet mission and the interstellar flyby missions used as the baseline in this study, it is optimum to use high specific impulses. Therefore, it is pointless to examine the use of beam-pushed sails for planetary mission; the energy efficiency is too low.

Energy efficiency is the single biggest difficulty of the laser (or microwave) sail concept. At a thrust of 6.7 newtons per gigawatt, gigawatt to terawatt lasers are required. This translates into extremely high costs unless more efficient and lower cost lasers are developed. While the high costs may be allowable for the interstellar flyby missions, where the high delta-V requirement means that rocket systems are ruled out due to mass ratio, and any conceivable propulsion system will have extremely high cost, they tend to make the lower velocity missions uneconomical to do with a laser-pushed sail compared to other propulsion systems.

The kinetic energy of the sail actually is robbed from the beam by the Doppler shift. When the sail is motionless, the Doppler shift is zero, and no energy goes into the sail. As the sail velocity increases, the beam is Doppler shifted proportional to the sail's velocity when it reflects. Therefore the efficiency of the sail in converting the energy of the beam into sail kinetic energy increases directly proportional to the velocity (in the non-relativistic case.)

For the case of a sail moving at a velocity which is slow compared to the speed of light, there is very little Doppler shift, and the reflected photons have nearly the same energy that they originally had. This introduces the concept that it may be possible to re-cycle the energy from the laser (or microwave) beam. The large size of the lens (or mirror) system required means that this may not be impossible to implement.

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